REPORT 403

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ADVISORY GROUP FOR AERONAUTICAL RESEARCH AND DEVELOPMENT

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A REVIEW OF IN-FLIGHT SIMULATION PERTINENT TO PILOTED SPACE VEHICLES

by

N. A. ARMSTRONG and E. C. HOLLEMAN

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NORTH ATLANTIC TREATY ORGANIZATION

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Neil A.Armstrong and Euclid C.Holleman

This Report was presented at the Twenty-First Meeting of the Flight Mechanics Panel of AGARD, held in Paris, 6-10 July, 1962

SUMMARY

This Report shows how the environment of actual flight may be used to simulate many phases of manned space exploration. A number of simulations using conventional, modified, and specially built aircraft are discussed in relation to the portion of space flight to which they are generally applicable, that is the launch, orbital, entry, or the landing-approach phase.

Inasmuch as this Report is a survey, only the scope of the investigations is indicated; no detailed descriptions of, or conclusions from, the research programs are given. Quantitative results may be extracted from the Papers mentioned in the references.

SOMMAIRE

Dans ce rapport les auteurs montrent de quelle manière les conditions environnantes du vol réel peuvent être utilisées pour simuler de nombreuses phases de l'exploration spatiale par engin piloté. Un certain nombre de représentations simulées à l'aide des avions classiques, modifiés ou spécialement construits dans ce but sont examinées en fonction de la partie du vol spatial à laquelle elles sont en général applicables, c'est-à-dire les phases de lancement, de vol orbital, d'entrée, d'approche à l'alunissage.

Etant donné qu'il ne s'agit dans ce rapport que de faire le point, seules les grandes lignes des études effectuées sont exposées, sans description détaillée du programme de recherches entrepris ni indication des conclusions établies. Des résultats quantitatifs peuvent être relevés dans les communications citées dans les références bibliographiques.

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A REVIEW OF IN-FLIGHT SIMULATION PERTINENT TO PILOTED SPACE VEHICLES

Neil A. Armstrong* and Euclid C. Holleman†

1. INTRODUCTION

The use of piloted flight simulations in spacecraft research has been widely reported, in the studies of References 1 and 2, for example. In Reference 2 the usefulness and limitations of ground-based flight simulators are discussed.

This Report shows how the environment of actual flight may be used to simulate many phases of manned space exploration. A number of simulations using conventional, modified, and specially built aircraft are discussed in relation to the portion of space flight to which they are generally applicable, that is the launch, orbital, entry, or the landing-approach phase.

Inasmuch as this Report is a survey, only the scope of the investigations is indicated; no detailed descriptions of, or conclusions from, the research programs are given. Quantitative results may be extracted from the Papers mentioned in the references.

2. LAUNCH PHASE

2.1 Pilot Control of Boost

The feasibility of manually piloting conventional multistage boosters from lift-off to orbital velocity is discussed in Reference 3. The piloting task is characterized by three problem areas: poor handling qualities (by conventional standards) in some flight regimes, stringent accuracy requirements in trajectory control, and a severe acceleration environment for the pilot.

The first problem is illustrated by the controllability plot of Figure 1. Typical booster configurations, represented by the area labeled 'basic booster', with low or negative static stability and low damping are predicted to be unsatisfactory or uncontrollable. The addition of simple rate damping moves the configuration farther from the uncontrollable boundary, but not into the satisfactory region. The controllability limits established on a ground-based simulator have been verified by actual flight with variable-stability aircraft at the points indicated. This work, with the addition of further ground simulator tests, has indicated that the handling qualities are satisfactory for the minimum maneuvering requirements of a boosted launch. The complexities of a variable-stability aircraft are not necessarily required for this type of investigation; more straightforward approaches, such as center-of-gravity control, are completely practical.

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The acceleration environment of typical large boosters was shown in the investigation of Reference 3 to be completely acceptable to pilots in good physical condition. In this program, the ability to perform a satisfactory control task under conditions of high acceleration was demonstrated on a centrifuge, but similar flight experience is limited. Trajectory control under conditions of high longitudinal acceleration is an objective of each flight of the X-15 research airplane. Although both the g-level (4+) and the time duration (80 to 130 sec) are modest, the task appears to be completely practical. Moderate increases in these parameters would not be expected to change this prediction.

2.2 Escape Maneuvers

It is well known that a high percentage of booster failures occurs at or near rocket-engine ignition. This has led to extensive interest in escape systems capable of successful operation from the pad. At lift-off, one concept for a currently proposed boost-glide vehicle utilizes a rocket engine with sufficient impulse to accelerate the entire winged vehicle vertically to a velocity and altitude from which conventional flared landings could be performed. The geometry of such a maneuver is illustrated in Figure 2. The glider is accelerated vertically to a speed from which the remainder of an Immelmann turn is completed. The aircraft is rolled from the inverted position to an upright position, and a conventional power-off approach (described later) to a nearby runway is performed.

When the practicality of such a maneuver (shown in Fig. 2) was questioned, the NASA Flight Research Center initiated a program[4] to demonstrate its feasibility. A conventional jet fighter was selected which, with minor modifications, could duplicate the lift-drag ratio of the glider. The lift-curve slope and wing loading were also close approximations of the hypothetical vehicle. It remained merely to devise a method of initiating the maneuver. By initiating a vertical pull-up along the path shown, energy conditions equal to those desired could be established at the point equivalent to that of rocket-engine burnout. At this point, the drag configuration of the simulated vehicle was established and the maneuver was performed. The results of the program indicated that trained pilots could successfully negotiate such a maneuver to a preselected landing spot with acceptable dispersions in touchdown point and touchdown velocity. In addition, a number of related areas were investigated, such as the establishment of the minimum-energy level (total rocket-engine impulse). The actual minimum-energy requirements for successful approaches were determined rather quickly in flight, and the analytical determination was then performed for correlation.

3. ORBITAL PHASE

3.1 Reaction Controls

Although a variety of attitude control systems can be expected to be developed for extended space flights in manned vehicles, continued extensive use of the rocket reaction control system may be anticipated. Reaction rockets for in-flight attitude control were first installed by the Flight Research Center in the X-1B research airplane in 1957. A more ambitious and extensive investigation was conducted with an F-104 aircraft in 1960. Proportional-thrust hydrogen-peroxide rockets were installed as shown in Figure 3. Two pitch and two yaw rockets were located in the nose of the

airplane with a hydrogen-peroxide tank and the appropriate plumbing. One roll rocket was located in each wing-tip pod, along with its respective fuel tank and plumbing. This technique eliminated the necessity of pumping dangerous hydrogen peroxide throughout the aircraft. The rockets could be controlled from an auxiliary left-hand control stick in the cockpit, integrated with aerodynamic controls through the center stick, or operated by rate gyros for auxiliary damping.

A typical trajectory for reaction-control research is shown in Figure 4. The pull-up from Mach 2 at an altitude of 40,000 ft is to as steep a flight-path angle as possible, so that the horizontal-velocity component and, hence, the dynamic pressure at the trajectory peak at about 90,000 ft are minimized. Although the engine is shut down over the top to prevent over-temperatures, the free-wheeling engine rotation is significant, and the gyroscopic coupling resulting from aircraft oscillations presents a challenging control problem. More than 1 min of useful test time is available in this maneuver, with a minimum dynamic pressure of approximately 10 lb/ft^2.

3.2 Systems Testing

The use of conventional aircraft for testing space systems or components can be extremely productive. System operations which are questionable in a force-free or 'weightless' state may be economically subjected to such an environment for limited periods of time in an aircraft.

Practical component-development work conducted at the Flight Research Center includes the cryogenic tankage test in an F-104 aircraft (Fig.5) which permitted 60 sec of zero-g ± 0.05 in any direction. The zero-g state may be more precisely attained by allowing the test package to float freely within a large volume of an aircraft flying a near-zero-g trajectory. The performance of the large aircraft required, however, limits such test periods to less than 15 sec. These test techniques lend themselves to basic research work also, as, for example, the joint NASA-University of Southern California project for investigating boiling heat transfer under force-free conditions.

Many spacecraft systems may be developed in conventional aircraft. For some mystifying reason, gyro drift rates may increase as much as one order of magnitude when a gyro is transferred from a laboratory bench to an aircraft. The advantages of flight testing of inertial systems are obvious. In a similar manner, such systems as the Doppler and optical may be economically demonstrated. Development projects of this type are planned with the X-15 research airplane including, for example, a star-tracking ultraviolet photography system such as that shown in Figure 6. The clamshell doors will be opened near the top of a 300,000-ft altitude trajectory, making it possible for an ultraviolet camera mounted on a stabilized platform to photograph a stellar reference at pilot command.

4. ATMOSPHERIC-ENTRY PHASE

It seems likely that most future manned spacecraft will be designed to be capable of atmospheric entry. Heretofore, all detailed designs have been for an earth entry, and this trend will predominate, of course, for some time to come. Entry problems may be categorized into three primary areas: structural and system integrity,

performance or energy management, and entry dynamics and controllability. Although all three areas lend themselves to flight simulation, only the latter, aircraft dynamics, has been extensively attempted in flight. This work can be attributed primarily to the development of the variable-stability aircraft.

4.1 Variable-Stability Aircraft

A variable-stability airplane is one in which selected stability and control derivatives are changed by augmenting the basic airplane values with variable increments produced by control-surface deflection proportional to an on-board computer which is fed by a number of sensors. A typical method used in creating such a research tool is described in Reference 5.

Our introduction to hypersonic handling qualities, to be sure, must be properly attributed to fixed-base simulation. It was such early investigations as the studies of References 6 and 7 that established the confidence required to initiate manned, controlled spacecraft programs. It became the province of the variable-stability aircraft, however, to add the required depth to these investigations to enable assessment of their significance. The usefulness of this type of airplane may best be shown by an example. Early in the X-15 program, before the aircraft's first flight, ground simulator tests had indicated that, without auxiliary roll damping, a lateral-directional divergence could be encountered under certain flight conditions. Inasmuch as these flight conditions would normally by transited on a standard entry maneuver, the technique required to negotiate this area with roll dampers inoperative received much investigation. Techniques attempted included 'quickening' of the pilot sideslip and roll attitude by adding yaw rate and roll rate, respectively, changing the stick-to-surface gearing, changing the basic aerodynamics by jettisoning the lower ventral tail, and introducing unconventional control techniques.

One unconventional technique, developed on a ground simulator, was based on the ability to control sideslip with ailerons. The first part of the time history (Fig.7) illustrates the destabilizing effect of conventional lateral-control inputs. In the latter part of the time history, a method termed the $\dot{\beta}$-technique is used. Sharp lateral-control motions are introduced in the direction of the airplane yaw at the time when sideslip is zero and sideslip rate is maximum. Hands-off flight between pulses insures minimizing instabilities introduced by inadvertent inputs. Since the X-15 is actually uncontrollable under these conditions when normal techniques are used, no roll-damper-inoperative flight data were anticipated from the program. However, extensive evaluation in this area has been provided by T-33 and F-100 variable-stability airplanes.

A comparison of the effectiveness of the $\dot{\beta}$ control technique on ground and flight simulators is shown in Figure 8. Pilot opinion, a variation of the well-known Cooper Scale of Reference 8, as a function of roll-damper gain is plotted as a solid line. The improvement afforded by the $\dot{\beta}$-technique on a fixed-base simulator is shown by the short-dashed line. Flight simulation in the F-100 aircraft, as represented by the long-dashed line, indicates that the improvement in handling qualities was greatly decreased as the roll-damper gain was reduced to zero. This reduction may be even greater when the bank-angle excursions must be minimized, as would be required in an entry. Furthermore, a lateral input in the wrong direction could be disastrous.

5. LANDING-APPROACH PHASE

Seldom has a problem been so elusive as the simulation of the landing approach. Although modest success has been achieved with low-angle, constant-speed approach simulations, the steep approaches characteristic of most space-vehicle configurations have defied successful ground simulation. The Flight Research Center has, therefore, relied primarily on in-flight simulation.

Early studies at the Flight Research Center (e.g. Ref.9) were directed toward defining practical approach paths of adequate lift-drag ratios. Later, a program[10] was initiated specifically to predict and determine a satisfactory technique for accurately and repeatedly landing the X-15. The low lift-drag ratio and high wing loading of this airplane combine to produce in the landing approach one of the most challenging aircraft ever flown. A standard F-104 aircraft is used to simulate the X-15 because of the similar characteristics of the airplanes, as shown in Figure 9. The lift-drag ratios plotted against airspeed are seen to compare favorably, which results in an accurate duplication of the flight-path descent angle. Fortunately, the lift-curve slopes and wing loadings are reasonable approximations, thus assuring acceptable turning and flare simulation. The techniques devised in the program have proved to be highly successful and are now consistently used as training maneuvers for X-15 pilots. The success of this simulation has led to a number of attempts to simulate higher-performance spacecraft.

5.1 Boost-Glide Configurations

The approach characteristics of the winged boost-glide aircraft (Fig.10) have received considerable attention at the Flight Research Center[11]. These configurations are, typically, highly swept delta configurations. Although the wing loadings and associated forward velocities are relatively low, the low lift-drag ratios create steep flight-path angles, high flare altitudes, and objectionably high sink rates close to the ground.

Two delta-wing fighter aircraft, the F-102A and F5D (Fig.11), have been used in landing-approach simulations. Their ranges of lift-drag ratio, lift-curve slope, and wing loading enable them to represent typical winged boost-glide configurations. Two typical approach paths are illustrated in Figure 12. The straight-in approach, developed in Reference 12, differs only in Phase I from the circular pattern. Phase I is that portion of the pattern in which the craft descends at essentially constant speed from a high-altitude reference point in the vicinity of the landing area to a low-altitude point referenced to the runway, arriving with a preselected amount of energy (airspeed). Both the circular and the straight-in techniques have proved to be satisfactory. The circular pattern affords somewhat more flexibility of operation in space positioning prior to arriving at the low-altitude reference point; whereas the straight-in approach has the advantage of reducing pilot-judgment requirements, necessitating only drag modulation to insure the proper airspeed.

Phase II is a flare maneuver that provides, for Phase III, a shallow, decelerating glide during which the landing configuration (e.g. landing gear and flap extension) is established.

Current extensions of these studies include restricted-visibility, night, and instrument approaches. For reduced-visibility approaches, transparent amber plastic inserts were attached inside the canopy of the test airplane with cutouts representing a desired optical field, as shown in Figure 13. By lowering a blue plastic visor over this helmet, the pilot could reduce his visibility to the field of view permitted by the cutouts only. If visibility became inadequate or local traffic precluded completion of the approach, he had merely to raise his visor, thus permitting immediate normal visibility.

5.2 Unconventional Configurations

Although extensive in-flight simulations of the landing approach of ballistic or lifting bodies have not been reported, some description of current and forthcoming work is appropriate.

Some lifting-body configurations (Fig.14) have subsonic lift-drag ratios which might permit a landing approach and horizontal landing similar to those previously described. A research glider, representative of this type of configuration, is being considered for construction.

The use of rotors for spacecraft approach and landing was proposed in Reference 13 and has recently received increased interest, with some development work being reported. In-flight simulation of this concept would appear to be necessary before it is committed to a future project.

The most widely reported recovery aid of the past year is the Rogallo wing, or paraglider (Fig.15), conceived by Mr. Francis Rogallo of the NASA Langley Research Center. This device, which may be described as something more than a steerable parachute, may provide lift-drag values as high as 4, is controllable both longitudinally and laterally, and may be flared for a horizontal landing[14]. The widespread applications of the vehicle include the possibility of use as the standard recovery technique for the Gemini and Apollo projects. The paraglider is controlled laterally and longitudinally by moving the center of gravity with respect to the wing center of pressure. No moving surfaces are required. Turning is accomplished by lateral control, with no yaw control required.

An unpowered glider (Fig.16) was constructed by the Flight Research Center in support of the Gemini project to develop the techniques required to perform an unpowered landing. It is towed aloft by a truck or light airplane and released in a manner similar to that used with a conventional sailplane. Wing loading, an important parameter because of the desire to minimize the size of the sail, has been varied; the configuration shown has a value of approximately 3.1.

Longitudinal performance characteristics of the Flight Research Center paraglider are shown in Figure 17. The maximum lift-drag ratio of 3.1 occurs at a lift coefficient equivalent to a steady-state glide velocity of 35 to 40 knots. Landing flares attempted from this flight condition are not successful, inasmuch as insufficient energy is available to arrest the vertical velocity. Landing flares to essentially zero sink rate have been performed from velocities of 45 to 50 knots. Although smooth-air control is satisfactory in both axes, gusty winds have a noticeably degrading effect on both longitudinal and lateral handling qualities. The knowledge gained from these simple, inexpensive test rigs can hardly be overestimated.

5.3 Lunar-landing Simulator

A successful earth simulation of the lunar-landing technique is one of the most challenging and potentially most fruitful projects of the current space programs. It is more difficult to perform than the simulations previously mentioned in that it must account for the 83% reduction in gravity and 100% reduction in atmosphere.

One approach, currently being considered by the Flight Research Center, to simulate the final several thousand feet of descent is shown in Figure 18. Although this simulator is to be constructed specifically for its task, it is singularly unsophisticated, not only for reasons of economy, but also in order to provide a quick route to the heart of the problem. A gimballed jet engine, at reduced throttle, provides an upward force along the gravity vector equal to 83% of the vehicle's earth weight. The vehicle is then accelerated toward the simulated lunar (earth) surface by a lunar-equivalent gravity. Rocket engines are used to decelerate the vehicle, provide stability and damping, and maneuver it for the final touchdown. After suitable techniques have been devised, a larger simulator, capable of carrying an actual lunar-landing capsule, could be used for developing the detailed hardware and pilot presentation used in the actual lunar descent. The in-flight training afforded lunar crews by such a vehicle would be invaluable.

6. CONCLUDING REMARKS

The use of in-flight simulation techniques can make a valuable contribution to manned spacecraft research. Investigations applicable to all phases of a space operation - launch, orbit, entry, and landing approach - have been successfully performed; however, an untold amount of similar work must still be done.

The most challenging projects for free-flight simulations lie in the future: the approach to the lunar surface, and the entry into foreign atmospheres. Significantly, the approaches and techniques required for such investigations are not new. They are closely allied to the methods which have been used in flight testing and flight research for many years. The time-tested combination of a bold invasion of an unknown area tempered with the caution born of years of experience can provide competent in-flight simulation of inestimable benefit to the exploration of space.

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NOTATION

C_L	lift coefficient (lift/qS)
g	acceleration due to gravity (ft/sec^2)
L/D	lift-drag ratio
M	Mach number
q	dynamic pressure (lb/ft^2)
S	wing area
V	velocity (knots)
α	angle of attack (deg)
β	angle of sideslip (deg)
$\dot{\beta}$	time rate of change of sideslip angle
γ	flight-path angle (deg)
δ_a	aileron deflection (deg)
ζ	damping ratio
φ	bank angle (deg)
ω_n	undamped natural frequency (1/sec)

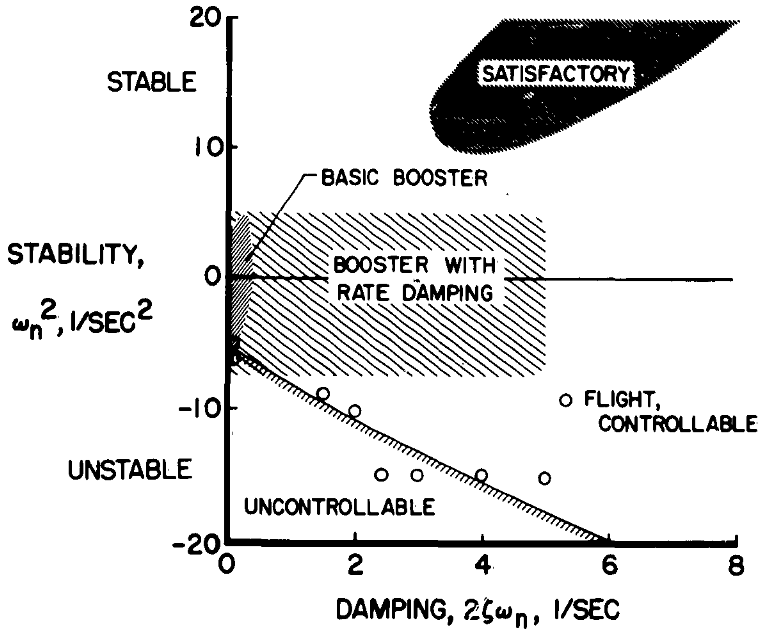

Fig. 1   Vehicle controllability

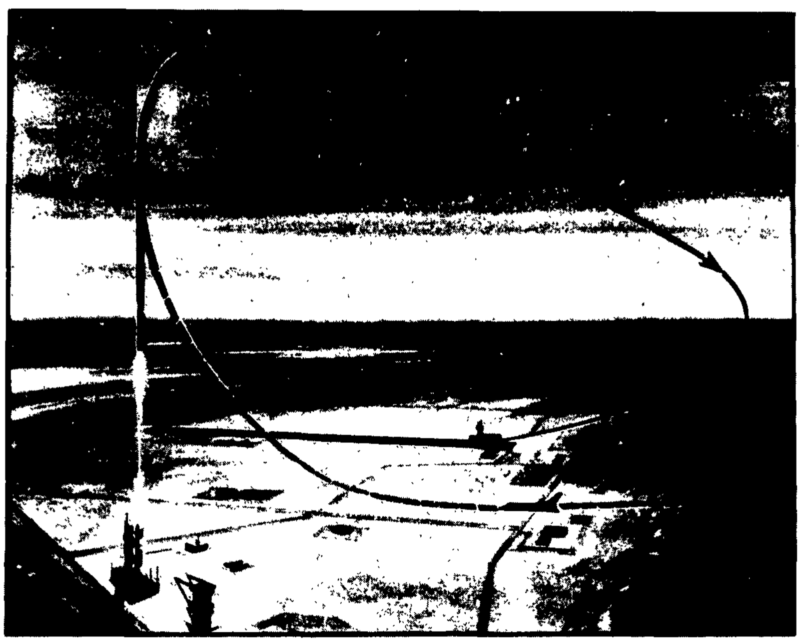

Fig. 2   Simulated abort

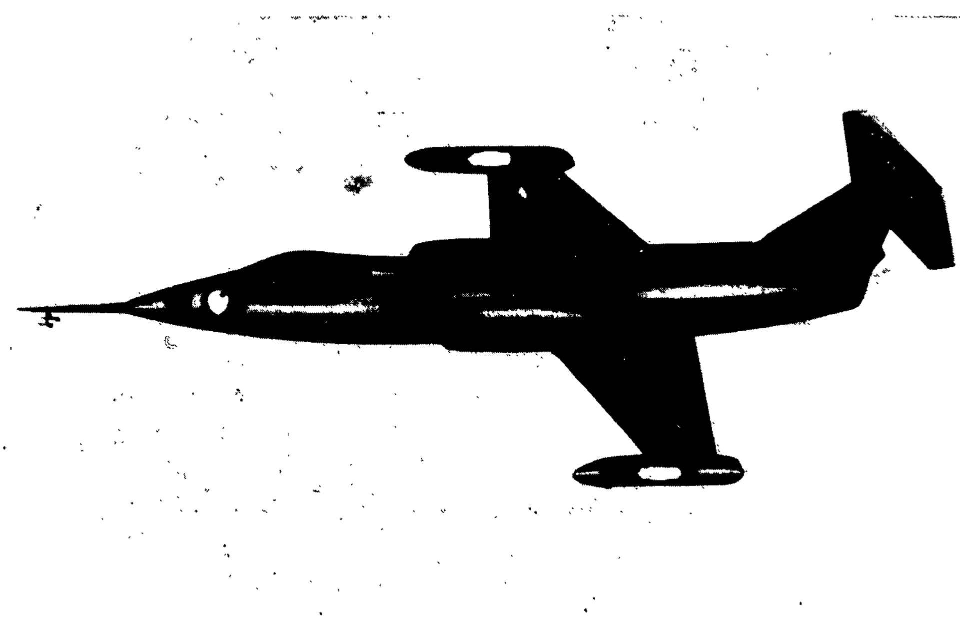

Fig.3 F-104 reaction-control vehicle

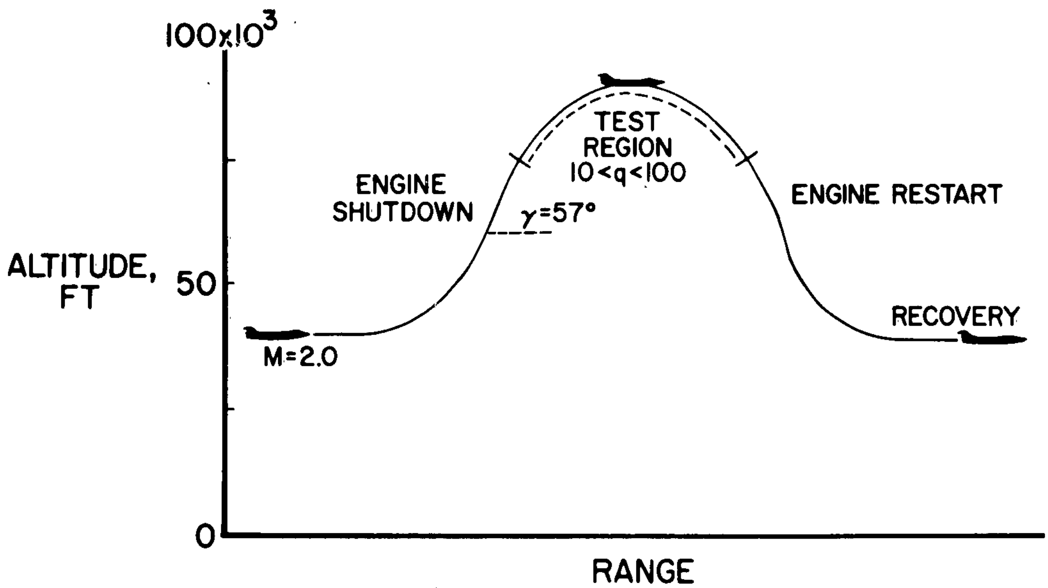

Fig.4 F-104 reaction-control maneuver

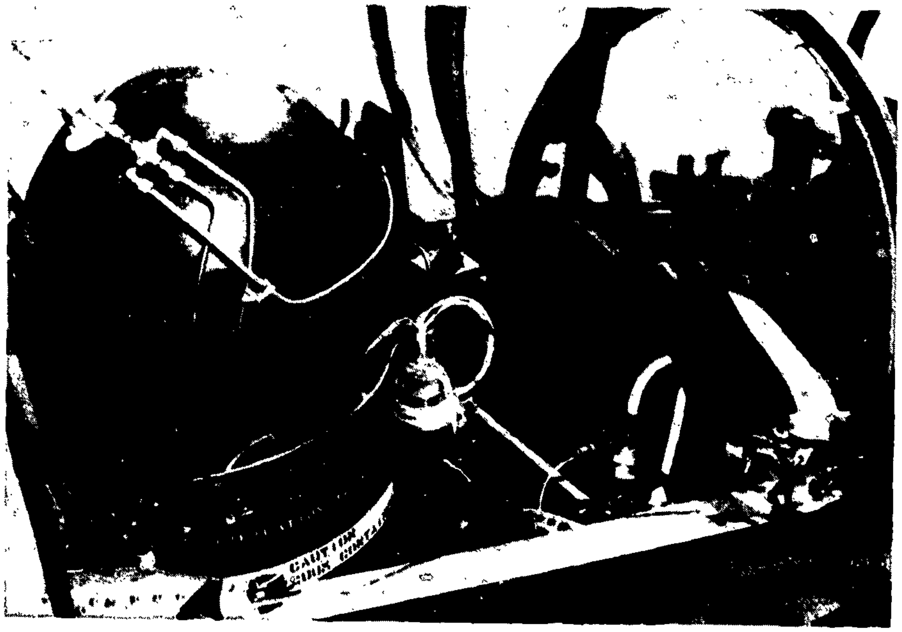

Fig.5 Liquid-nitrogen tank in F-104

Fig.6 X-15 instrument-compartment modification (Skylight)

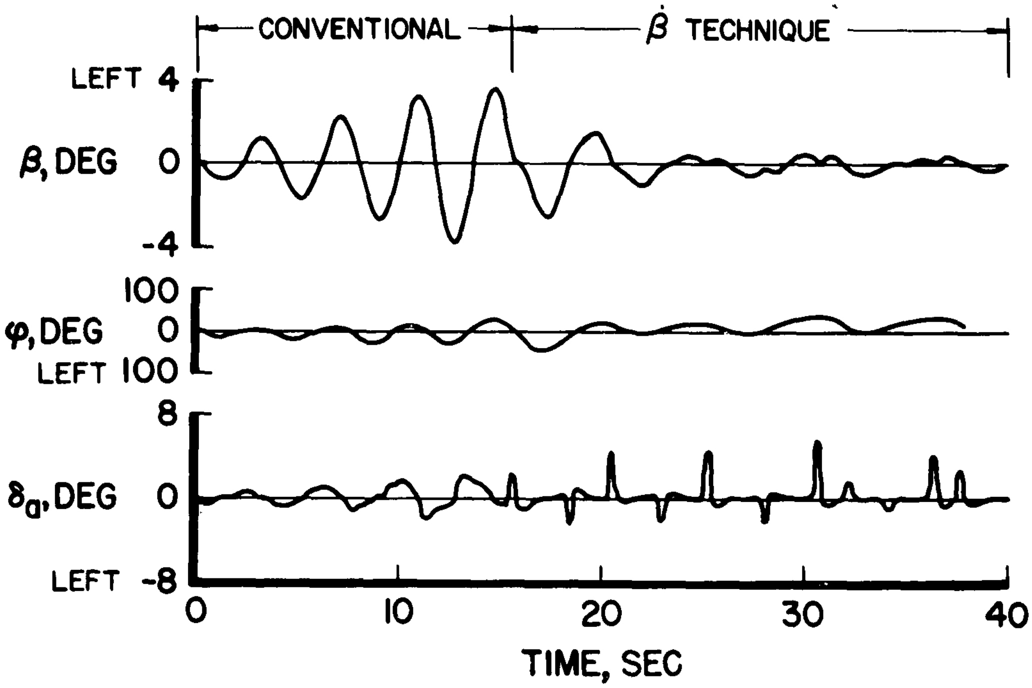

Fig.7 Illustration of $\dot{\beta}$ control technique. Fixed-base X-15 simulator

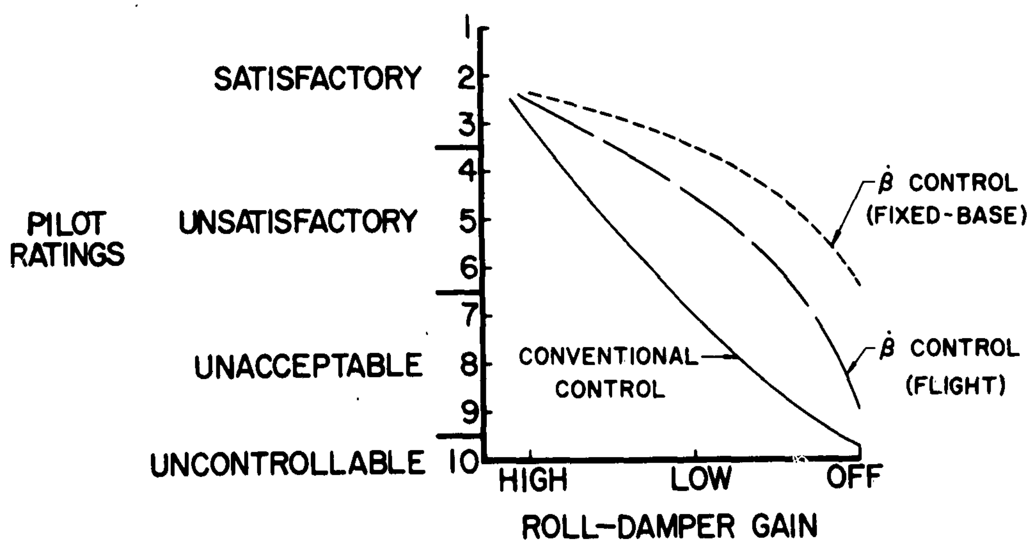

Fig.8 Effect of motion cues on $\dot{\beta}$ control technique. Center stick, $M = 3.5$, $\alpha = 10^{\circ}$

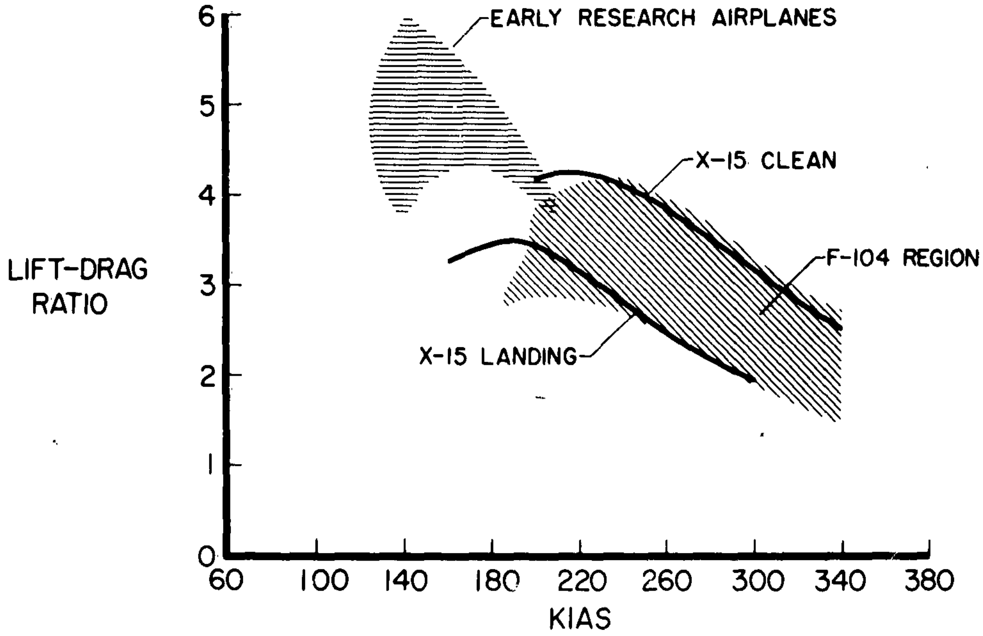

Fig.9 F-104 simulation of X-15 landing

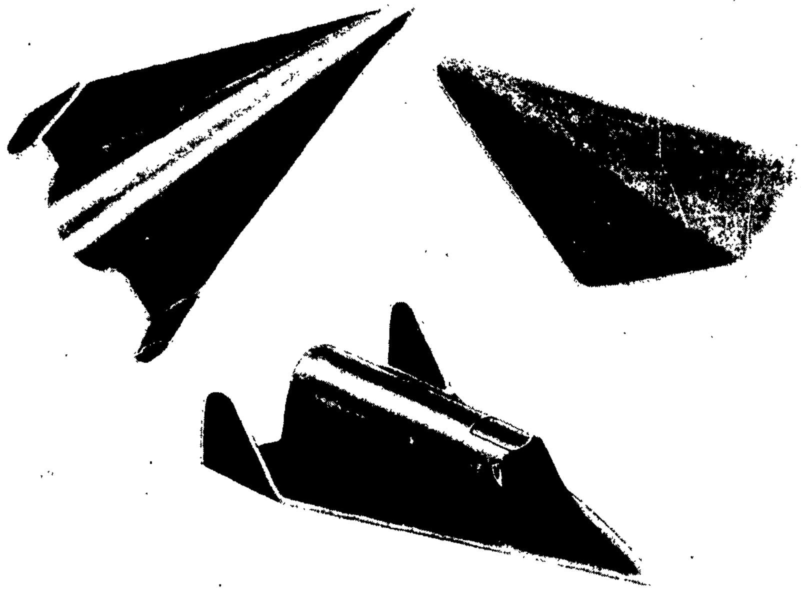

Fig.10 Winged boost-glide configurations

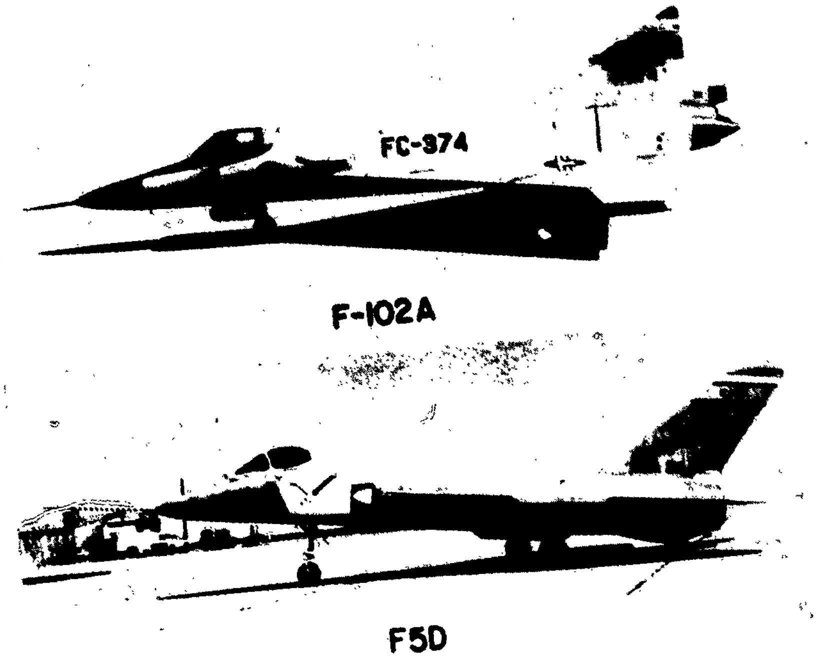

Fig.11 Aircraft used to simulate landing approach

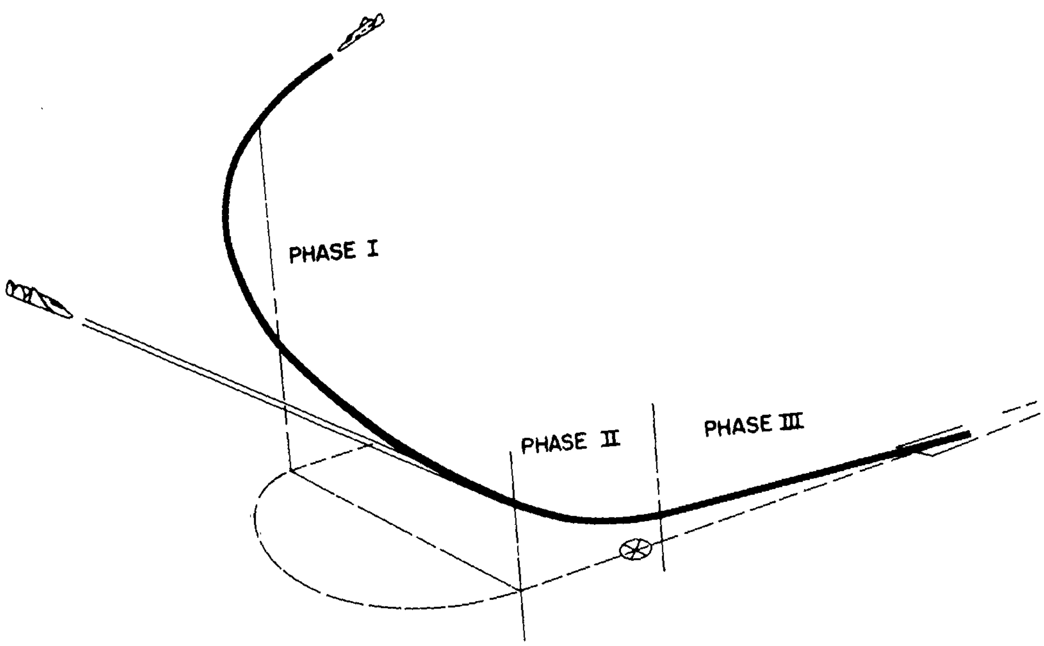

Fig.12 Landing-approach paths

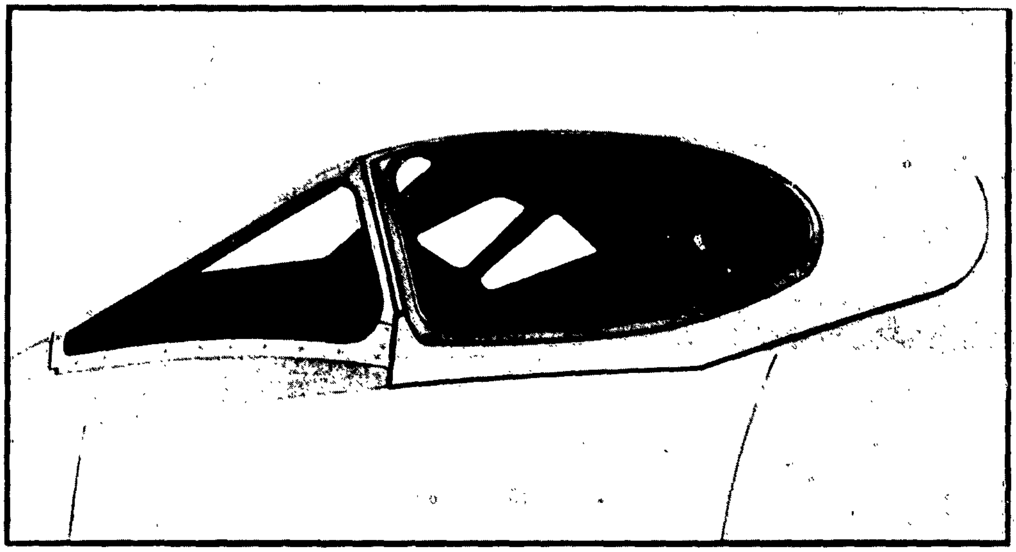

Fig.13 Canopy with reduced visibility

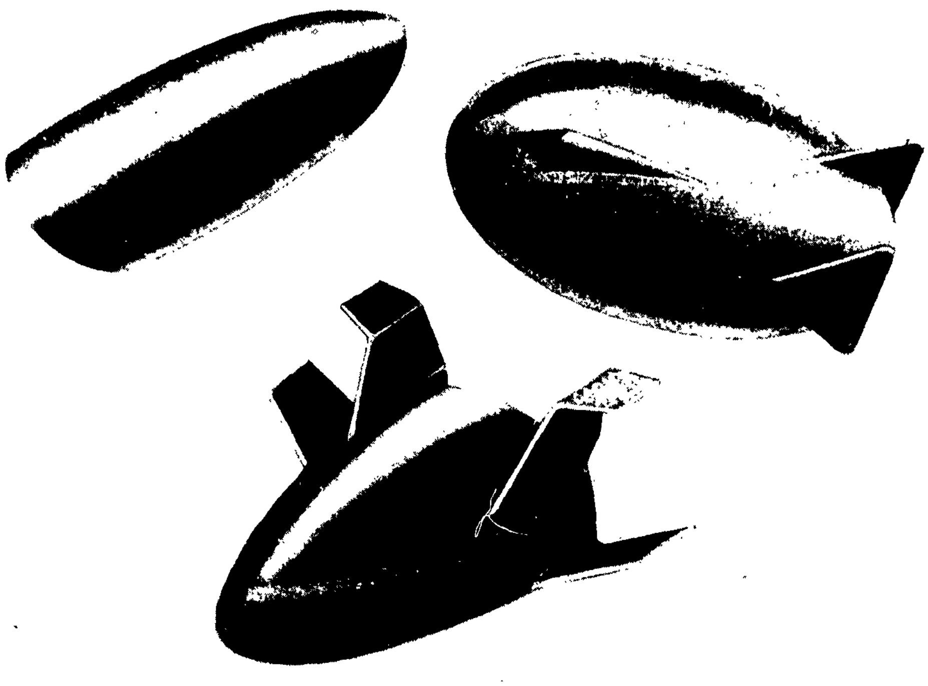

Fig.14 Lifting-body configurations

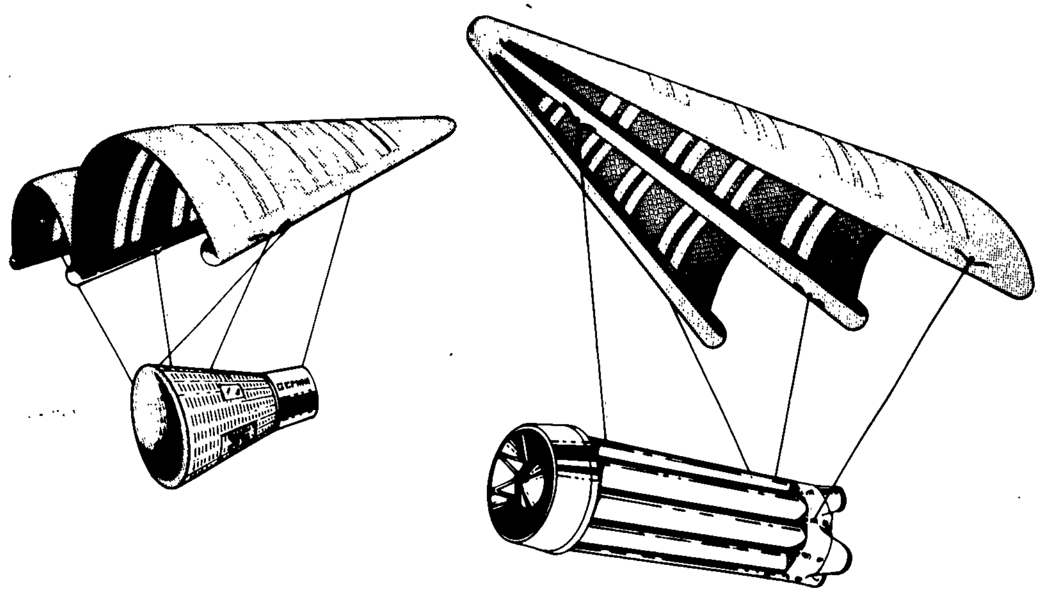

Fig.15 Rogallo-wing concept

Fig.16 FRC Paraglider

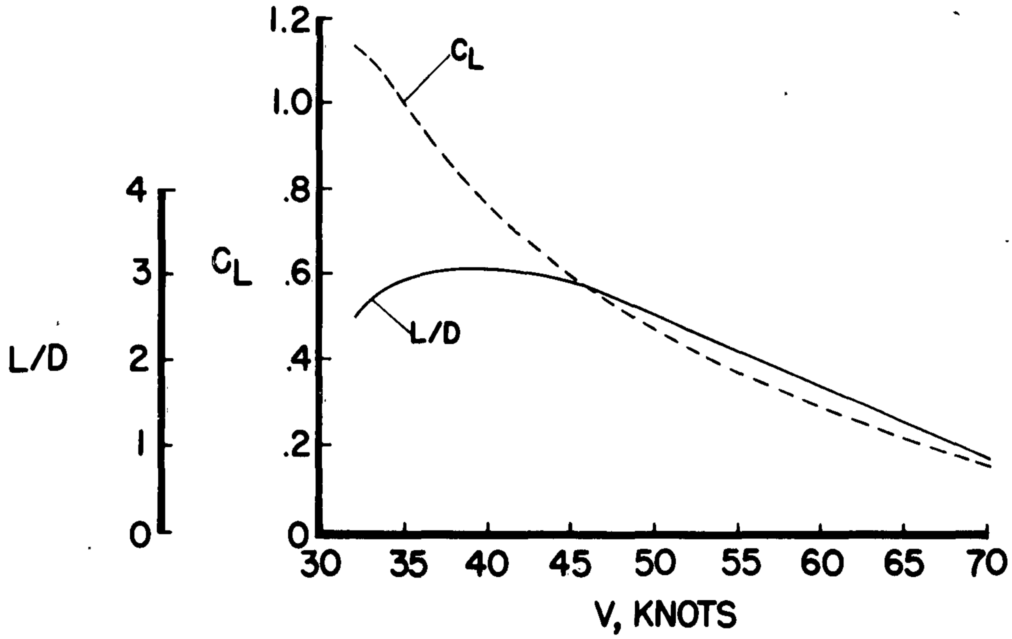

Fig. 17 Longitudinal performance of the FRC paraglider

Fig. 18 Lunar-landing simulator

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